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# Static and Dynamic Compression of Earth Materials

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The triennium, 1967–1970, has been a period of marked increase in acquisition of pressure-volume data for minerals, rocks, and compounds of geophysical interest. A wide assortment of data has been obtained by the conventional dilatometric techniques as well as by the more recently developed X-ray diffraction and shock-wave techniques. Highlights of progress during the last 3 years include hydrostatic compression measurements for Apollo 11 lunar samples [Stephens and Lilley, 1970; Schreiber *et al.*, 1970], static compression measurements of the spinel phase of  $(\text{Mg,Fe})_2\text{SiO}_4$  solid solutions, which are likely constituents of the transition zone of the earth's mantle [Mao *et al.*, 1969], and Hugoniot data for high-pressure phases of ferromagnesian silicates, which may represent the constituents of the lower mantle [McQueen *et al.*, 1967b].

## Static Compression

Isothermal static compression of minerals (including elements) has been conducted by two different techniques: the X-ray diffraction methods for powdered specimens, and the dilatometric methods for polycrystalline aggregates and single-crystal specimens. The X-ray diffraction methods have been used for a study of milligram-size powdered crystalline samples, and the dilatometric methods have been used exclusively for static compression studies of rocks and aggregates.

A variety of designs for X-ray diffraction high-pressure cells are currently in use in the United States. They include diamond-anvil cells [Bassett *et al.*, 1967; Weir *et al.*, 1969], tungsten carbide Bridgman anvil cells [Jamieson, 1965; McWhan and Bond, 1964], supported tungsten carbide anvil cells [Perez-Albuerne *et al.*, 1964; Freud and Sclar, 1969; Freud and LaMori, 1969], and a tetrahedral tungsten carbide cell [Barnett and Hall, 1964]. Recent advances in X-ray techniques are summarized by McWhan [1969]. Accuracies of  $\pm 0.1\%$  in

lattice parameter and, hence, of  $\pm 0.3\%$  in volume, under high pressures, have been attained by these methods.

The pressures imposed on powdered specimens in these high-pressure cells are determined by using 'pressure markers' or internal pressure standards such as NaCl or Al for which the pressure-volume ( $P$ - $V$ ) isotherm are assumed to be known. Drickamer *et al.* [1966] use Ag, Al, Mo, Nb, Pd, or V as a standard. The isotherms for these materials were obtained from the reduced Hugoniot data of Rice *et al.* [1958]. Other investigators prefer NaCl, since its equation of state has been extensively studied by shock, static, and ultrasonic methods. The pressure indicated by the lattice parameters of the internal pressure standard, which is mechanically mixed with the sample, is often assumed to be equal to the pressure applied on each grain of the sample. In certain cases, e.g., NaCl and Nb metal powder compressed between Bridgman-type tungsten carbide anvils, Jamieson and Olinger [1968a, b] have shown that this assumption is not always valid. Hence, care must be exercised to assure that complete flowage of the pressure medium around each sample grain has occurred when performing X-ray experiments.

The  $25^\circ\text{C}$  isotherm of NaCl has been calculated up to several hundred kilobars by Decker [1965, 1966] using the Mie-Grüneisen equation and the Born-Mayer interionic potential, by Perez-Albuerne and Drickamer [1965] and Weaver *et al.* [1968] using the Hildebrand equation and the Born-Mayer type interionic potential, and by Thomsen [1970] using a fourth-order anharmonic equation derived from the finite strain theory. This isotherm has also been calculated by Christian [1957] and Fritz *et al.* [1968] from Hugoniot data for NaCl. (The Hugoniot data of Christian and Fritz *et al.* agree with those of Al'tshuler *et al.* [1961] and Hauver and Melani [1970].) With the exception of Decker's isotherm, the theoretical  $25^\circ\text{C}$  isotherms, the isotherms of Perez-Albuerne *et al.* and Weaver *et al.*, and those reduced from Hugoniot data agree to within about 10 kb at 300 kb. Decker [1965, 1966] used a bulk modulus value of 234.2 kb ( $25^\circ\text{C}$ ) instead of the current best value of  $237.5 \pm 1.5$  kb. If his equation is corrected for the initial bulk modulus, it yields  $P$ - $V$  relations that are in agreement with the others. The new isotherms for NaCl also agree with the 100-kb static compression data of Bridgman [1945].

The  $P$ - $V$  relationship for NaCl can also be compared with the fixed points in the pressure scale established by using such first-order phase transformations as those in Bi, Tl, and Ba. The phase transformation pressures for those materials have been accurately determined by Kennedy and LaMori [1962], Heydemann [1967], Haygarth *et al.* [1967], and Haygarth *et al.* [1968]; the volumes of NaCl at these transformation pressures have been determined by Jeffery *et al.* [1966] up to 80 kb.

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Weaver *et al.* [1968] have shown that the fixed points pressure scale agrees with the NaCl isotherm within the experimental and calculational uncertainties. The consistency of the pressure scale was tested by determining the isotherm for MgO with X-ray techniques by McWhan [1967] up to 120 kb and by Weaver *et al.* [1968] up to 280 kb. Since MgO compresses to a  $V/V_0$  value of 0.87 at 300 kb, a reliable compression value for MgO can be computed with the Birch-Murnaghan or Murnaghan equations using the bulk modulus  $K_0$  and  $K_0'$  ( $=\partial K/\partial P$ )<sub>T</sub> evaluated at zero pressure) measured ultrasonically in single crystals [Anderson and Andreatch, 1966; Spetzler, 1970]. The NaCl isotherm calculated by the above investigators is consistent with the MgO isotherm within the experimental uncertainties up to 280 kb, the highest pressure tested. On the basis of the experimental and the theoretical evidence, it is not yet possible to determine which of the currently available isotherms for NaCl is most reliable. Thus, at present, the NaCl pressure scale for room temperature appears to be known within  $\pm 3\%$  in pressure up to 300 kb. Above 300 kb NaCl transforms to a high-pressure polymorph having a simple cubic B2, or CsCl structure [Bassett *et al.*, 1968]. More refined measurements of the elastic properties of NaCl, as well as improvement in the theories on the effect of pressure and temperature on the Grüneisen parameter, are necessary for further improvement of the pressure scale. Recent progress in high-pressure standards and calibrations are reviewed by Decker *et al.* [1969].

The Murnaghan trajectory for Au calculated by using the  $K_0$  and  $K_0'$  values of Barsch and Chang [1967] was used as a standard in dilatometric compression measurements by Vaidya and Kennedy [1970] and others. Grover [1970] compared the isothermal compression data of Vaidya and Kennedy [1970] for eighteen metals to 45 kb with the 25°C isotherms reduced from the available shock Hugoniot data. He concluded that the static compression data of Vaidya and Kennedy, the sound velocity data, and the shock Hugoniot data are mutually consistent within 2% in pressure up to 45 kb. The  $P$ - $V$  relationships for Au and NaCl, which are used as the standards for static compression measurements, appear to be consistent with those determined from the shock and ultrasonic data.

A symposium on measurements of high-pressure environment was held in October 1968 under the sponsorship of the U.S. National Bureau of Standards and the Geophysical Laboratory, Carnegie Institution of Washington. The highlights of this symposium are briefly described by Lloyd *et al.* [1969], and the complete proceedings are currently in press.

McWhan [1967] determined the effect of pressure on the lattice parameters of  $\alpha$ -quartz at room temperature up to 150 kb, using a Bridgman carbide anvil high-pressure cell and the Guinier focusing geometry for X-ray diffraction. Bassett and Barnett [1970] measured the effect of pressure on the lattice parameters of synthetic coesite and stishovite up to 85 kb, using a tetrahedral press X-ray diffraction apparatus. Liu *et al.* [1969] measured the effect for synthetic stishovite up

to 220 kb, using a diamond-anvil press and the Debye-Scherrer X-ray diffraction geometry.

Mao *et al.* [1969] studied the effect of pressure on the lattice parameter of wüstite ( $\text{Fe}_{0.924}\text{O}$ ), the spinel ( $\gamma$ ) phase of  $\text{Fe}_2\text{SiO}_4$ ,  $(\text{Fe}_{1.8}\text{Mg}_{0.2})\text{SiO}_4$ , and  $(\text{Fe}_{1.6}\text{Mg}_{0.4})\text{SiO}_4$  up to 255 kb at room temperature using a diamond anvil X-ray diffraction camera [Bassett *et al.*, 1967]. The bulk modulus value of  $2.0 \pm 0.1$  Mb calculated for these three spinels ( $\gamma(\text{Fe,Mg})_2\text{SiO}_4$ ) is consistent with the recent ultrasonic measurements by Mizutani *et al.* [1970]. The spinel phase of  $\text{Ni}_2\text{SiO}_4$  was also studied by Mao *et al.* [1970] up to 300 kb, and a bulk modulus value of  $2.14 \pm 0.07$  Mb was reported.

Solid solutions of almandite ( $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ )—pyrope ( $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ) were investigated by Takahashi and Liu [1970] up to 328 kb at room temperature, using a diamond anvil X-ray diffraction camera. A systematic increase in the bulk modulus with increasing Mg content was observed and a thermodynamic relationship between the bulk modulus and chemical composition was reported.

Mao *et al.* [1967] studied the compression of pure iron up to 300 kb at room temperature, using a diamond anvil X-ray diffraction camera. The volume change associated with the bcc-hcp phase transformation was determined to be  $-0.34 \pm 0.01 \text{ cm}^3/\text{mole}$ . This change is nearly twice as large as reported on the basis of the earlier Hugoniot data. The bulk modulus for the high-pressure hcp phase was experimentally indistinguishable from that of the low-pressure bcc phase. Silberman [1967] studied the effect of pressure on Fe-7.2%Si alloy and  $\text{FeSi}_3$  up to 290 kb at room temperature, and Takahashi *et al.* [1968] studied the effect of pressure on Fe-5%Ni and Fe-10%Ni alloys up to 308 kb at room temperature. The effect of pressure on the bcc-hcp phase transformation in iron alloys, and the effect of the alloying elements on the bulk moduli, in both structures are discussed.

Drickamer and his associates have conducted an extensive survey of the effect of pressure up to 300 kb at room temperature on the lattice parameters of numerous compounds, using a supported carbide anvil high-pressure cell and Debye-Scherrer geometry [Perez-Albuerne *et al.*, 1964]. The materials of geophysical interest studied by Drickamer and his associates include  $\text{Fe}_{1-x}\text{O}$ ,  $\text{SnO}_2$ ,  $\text{MnO}_2$ ,  $\text{TiO}_2$ ,  $\text{MnS}$ , and  $\text{FeS}_2$  [Clendenen and Drickamer, 1966a],  $\alpha\text{Fe}_2\text{O}_3$ ,  $\text{Cr}_2\text{O}_3$  [Lewis and Drickamer, 1966],  $\text{Al}_2\text{O}_3$  [Hart and Drickamer, 1965],  $\text{CaO}$ ,  $\text{MgO}$  [Perez-Albuerne and Drickamer, 1965], diamond, graphite [Lynch and Drickamer, 1966], Fe-8%Si, and  $\text{Fe}_3\text{Si}$  [Clendenen and Drickamer, 1966b]. The results of the studies by Drickamer and his associates are summarized in Drickamer *et al.* [1966].

The effect of pressure on the lattice parameters of the  $\alpha\text{PbO}_2$  phase of  $\text{TiO}_2$  was investigated by Jamieson and Olinger [1968a, b] up to 200 kb at room temperature, using a Bridgman anvil cell and Debye-Scherrer X-ray diffraction geometry. An increase of the dimension of the unit cell along the  $c$  axis with pressure was observed up to 120 kb, whereas little change was observed in the  $a$  axis dimension.

*Barnett et al.* [1969] investigated the effect of pressure on  $\text{NaNO}_3$ , using a tetrahedral anvil X-ray diffraction apparatus [*Barnett and Hall*, 1964] and determined the linear and bulk compressibilities up to 85 kb. They observed anomalous line intensity changes near 45 kb. This change was attributed to a transition from R3c space group to R3c with no measurable discontinuity in volume. They infer that this higher-order transition represents rotation of the nitrate groups in alternate layers along the trigonal axis in opposite directions with increasing pressure. At high pressures the nitrogen positions are no longer planar with the oxygen atoms. Although the analogous change in atomic arrangements has not been experimentally demonstrated in silicate minerals, it is likely to occur with compression. If this type of rotation occurs, it would greatly affect the bulk modulus of silicates at high pressures.

*Brace et al.* [1969] determined the isothermal compressibility of kyanite, andalusite, and sillimanite by using a strain gage method [*Brace*, 1964] in a hydrostatic medium up to 10 kb and a solid medium piston-cylinder apparatus [*LaMori*, 1967] up to 40 kb. The specimens studied were all hot pressed aggregates of (1:1) silicate/Cu or silicate/Pb mixtures. The compressibility values of the silicate specimens were obtained by subtracting the effect of the Cu or Pb matrix from the bulk compression for the mixture. They obtained a compressibility value of  $0.77 \pm 0.04 \text{ Mb}^{-1}$  for all three materials at 1 bar and  $25^\circ\text{C}$  and could not detect the significant differences between these minerals.

*Vaidya and Kennedy* [1970] measured the effect of pressure on the volume of eighteen metals up to 45 kb at room temperature, using a piston-cylinder apparatus and Au as the standard. A precision of 0.0005 in  $V/V_0$  for less compressible materials and of 0.0015 in  $V/V_0$  for more compressible materials were achieved. Differences of up to 10% between their initial compressibility values and the values obtained by *Bridgman* [1940, 1949] were found.

*LaMori* [1967] obtained static compression data for twenty rocks and minerals up to 36 kb in a temperature range of 22 to  $450^\circ\text{C}$  using a piston-cylinder apparatus with Au or Pb as the pressure medium. The results of these experiments give significantly lower compressibilities than were obtained by means of other experimental methods, such as the pulse-echo ultrasonic method up to 10 kb. Such differences were attributed to the existence of pores in specimens at 10 kb.

*Stephens and Lilley* [1968] have measured the static compression of Apollo 11 lunar crystalline rock, microbreccia, and dust specimens up to 40 kb, using a piston-cylinder apparatus. They found that the intrinsic compressibility for the lunar dust is about  $1.28 \text{ Mb}^{-1}$  and is similar to that for quartz and feldspar. *Schreiber et al.* [1970] investigated static compression behavior for a vesicular fine-grained crystalline rock collected on the Apollo 11 mission, using a hydrostatic apparatus [*Brace*, 1965] to 6 kb. They found that the compressibility value for this rock specimen,  $1.98 \text{ Mb}^{-1}$  at 5 kb, is closer to acidic rocks than to basic rocks.

## Dynamic Compression

In the area of shock compression, notable advances in the use of high-performance light gas, compressed gas, and propellant gun technology to launch shock generating flyer plates, at speeds that are difficult to achieve with high explosives (below 2 km/sec and above 5 km/sec), has taken place [*Jones et al.*, 1966; *Linde and Schmidt*, 1966; *Lower and Ahrens*, 1969; *Morgan*, 1969; and *Fowles et al.*, 1970].

New Hugoniot data for a series of crustal and possible mantle type rocks (granite, diabase, dunite, eclogite, and bronzitite), monomineralic feldspar rocks, and a series of oxides and mixed oxides, have been reported to pressures in excess of 1 Mb by *McQueen and co-workers* [*McQueen and Marsh*, 1966; *McQueen et al.*, 1967b]. Hugoniot data for feldspars, granite, basalt, sandstone, and limestone and rutile are also reported in *Ahrens et al.* [1969a, b], *Shipman* [1969], *Jones et al.* [1968], *McQueen et al.* [1967a], and *Linde and DeCarli* [1969]. All but the data for four oxides,  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{SnO}_2$ , and  $\text{MnO}_2$ , of the more than twenty silicate rocks, silicate minerals and oxides, and mixed oxide compounds tested show convincing evidence for shock-induced transitions to one or more denser phases or phase assemblages. Typically, the silicates display three distinct regimes along the Hugoniot: a low-pressure regime in which the Hugoniot represents states in the untransformed material and in which correlations with low-pressure ultrasonic data are possible; a mixed phase regime representing shock states that comprise a mixture of initial and transformed (high-pressure phase) minerals; and a high-pressure regime characterizing the equation of state usually of a denser high-pressure phase or phases.

The Hugoniot data in the high-pressure regime for Twin Sisters and hortonolite dunites [*McQueen et al.*, 1967b], which at ambient pressure are largely composed of olivines with the compositions  $(\text{Mg}_{0.88}, \text{Fe}_{0.12})_2\text{SiO}_4$  and  $(\text{Mg}_{0.44}, \text{Fe}_{0.56})_2\text{SiO}_4$  [*Mao et al.*, 1970], are of special significance to the study of the earth's interior. From the high-pressure data for these dunites *McQueen et al.* [1967b] constructed metastable Hugoniots that bracketed the seismologically determined density-depth profiles in the lower mantle. This and an earlier correlation of the densities of the high-pressure oxide and silicate shock data with the density of the lower mantle by *Birch* [1964] have motivated intensive analytic study of these data.

Because the high-pressure phase Hugoniot data are available, in most cases in the range of 400 to over 1000 kb, and hence, display substantial compressions, the use of at least a third-order equation of state relating Helmholtz free-energy and volume, centered at ambient pressure, is appropriate. To construct such an isothermal or isentropic equation of state, a minimum required set of three parameters would be the zero pressure density  $\rho_0$  and the appropriate bulk modulus  $K_0$  at constant entropy or temperature, and the pressure derivative of  $K$ ,  $K'_0$ . With the usual availability of only 4 to 15, or so, data points, and with the experimental scatter taken into account, the data set is not, in general, capable of

independently yielding three parameters with acceptable uncertainties. (Of the class of silicates and oxides that undergo a shock-induced phase change, only for  $\text{SiO}_2$  (stishovite) are the zero pressure density and other thermodynamic properties measured.) Additional constraints to the equation of state of the high-pressure phases, relating the zero pressure bulk modulus  $K_0$  and  $\rho_0$  of the form

$$K_0 = a\rho_0^{1/2} + b\rho_0^{3/2}$$

and

$$K_0 = \rho_0^{1+1/n} \cdot (A\bar{M})^{1/n}$$

have been proposed by Wang [1967] and Anderson and Kanamori [1968]. Here  $a$ ,  $b$ ,  $n$ , and  $A$  are empirical parameters. The first expression is similar to Birch's [1961] linear relation between compressional-wave velocity and density at constant mean atomic weight ( $\bar{M}$ ). The second, the seismic equation of state, SEOS, was proposed by Anderson [1967]. Both formulas fit a considerable body of ultrasonic data with similar variances. The first equation has the advantages that a similar form of the equation can also predict shear velocities fairly well; the second has the advantage that it explicitly treats the effect of changing mean atomic weight. Initially, Wang [1967], using the first equation, fit the shock data of McQueen and his co-workers by assuming a linear shock velocity-particle velocity type equation of state [McQueen et al., 1970] and neglecting transitional energy and thermal effects. He concluded that the bronzites transformed to stishovite plus a spinel phase and the dunites transformed to spinel structure. Later, taking into account shock heating but not transitional energies, Wang [1968a, b] again analyzed the shock data and concluded that on comparison with seismic results that the Twin Sisters dunite had slightly less  $\text{Fe}^{2+}$  than the rocks of the lower mantle. In the analysis of Anderson and Kanamori [1968], following McQueen et al. [1963], a series of metastable Hugoniot's were constructed by using the Birch-Murnaghan form for the equation of state and the SEOS to constrain the zero pressure densities. Revised separate values for  $A$  and  $n$  parameters appropriate for application to different mineral classes have recently been proposed by Anderson [1969]. Later analysis by Ahrens et al. [1969a] employed a similar approach, but the  $\rho_0$ - $K_0$  constraint was applied to the calculated high-pressure phase isentrope and phase transition energies were separately estimated from thermochemical data. They inferred transformations to the following probable crystal structures (on the basis of the calculated zero pressure densities, the densities of silicates and of analog compound phases quenched from high pressure, and from crystal-chemical arguments):  $\text{MgAl}_2\text{O}_4$  (spinel) to calcium ferrite structure, feldspars to hollandite structure, olivines to strontium plumbate structure, pyroxenes to ilmenite structure, kyanite, sillimanite, and andalusite to corundum plus stishovite,  $\alpha\text{Fe}_2\text{O}_3$  (hematite) to the perovskite structure, and

$\text{TiO}_2$  (rutile) to fluorite structure. Linde and DeCarli [1969] have considered the transformation of  $\text{TiO}_2$  to fluorite structure in detail and conclude that the density of  $\text{TiO}_2$  in the fluorite structure ( $\sim 4.1 \text{ g/cm}^3$ ) would be much lower density than the values obtained by McQueen et al. [1967a] ( $5.65 \text{ g/cm}^3$ ) and Ahrens et al. [1969a] ( $5.71 \text{ g/cm}^3$ ).

To reduce Hugoniot data to other forms of the equation of state such as isotherms, isentropes, or, for phase changes, metastable Hugoniots, knowledge of the Grüneisen parameter,  $\gamma = V(\partial P/\partial E)_V$ , and its variation with volume, and possibly internal energy ( $E$ ), is required. For cubic metals at temperatures below those at which electronic specific heat must be taken into account (e.g.,  $10,000^\circ\text{K}$ ), and above the lattice Debye temperature, the formalism developed by Pastine and Forbes [1968] can be applied. Their development permits calculation of  $\gamma$  as a function of  $V$ , directly from the Hugoniot data and supplementary data on specific heat, thermal expansion, and elastic constants (and derivatives of elastic constants with pressure). Where minerals do not undergo phase changes, the Hugoniot data may also be reduced by calculating the initial Grüneisen ratio from thermochemical data and determining its initial variation with compression from the thermodynamic formulas given by Bassett et al. [1968]. The results obtained by Wang [1968], Ahrens et al. [1969a], Carter et al. [1968], and Grover [1970] demonstrate that, where a phase change does not occur, the variations in the equation of state obtained from different assumptions regarding how  $\gamma$  decreases with volume, are minor. Anderson [1968] has compared the variation of  $\gamma$  obtained from several theories. Where there is a shock-induced phase change in a mineral, with the exception of stishovite [Ahrens et al., 1970], no explicit data, or relevant theory, giving the Grüneisen ratio of the high-pressure phase now exist. Various workers have employed the Slater [Anderson and Kanamori, 1968], Dugdale-McDonald [Ahrens et al., 1969a], and  $\gamma/V = \text{constant}$  [McQueen et al., 1967b; Wang, 1968] assumptions. Knopoff and Shapiro [1969] have recently summarized the difficulties in each of these approaches. One promising, although experimentally difficult, technique for obtaining Grüneisen ratio data at high pressure is the application of Hugoniot curves for material centered at different initial porosities. Analysis of such data have been made for porous  $\text{MgO}$  [Carter et al., 1968] and initially porous  $\alpha$  quartz in the stishovite regime [Ahrens et al., 1970].

Recently, some measurements of isentropes, centered at high pressure, i.e., adiabatic release curves, have been performed by novel shock-wave techniques. Such data are useful in porous rocks, such as in tuff [Lysne, 1970] and weathered tonolite [Petersen, 1970]. Release isentropes in such crystalline materials as plagioclase [Ahrens et al., 1969b] and quartz [Ahrens and Rosenberg, 1968] have also been reported. Another area of recent activity has been the study of dynamic yielding under shock compression. A host of interesting and challenging problems remain in this,  $<100\text{-kb}$  regime. Data for various oxides and silicates have been reported

by Ahrens *et al.* [1968], Jones and Froula [1969], and Ahrens and Linde [1968].

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## Melting Relations

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The process of magma generation with subsequent uprise and intrusion or extrusion of magma is one of the fundamental processes in the evolution of the earth. Rheological and other physical properties change markedly wherever and whenever partial melting occurs. The melting relations of minerals and rocks can now be measured in the laboratory to pressures corresponding to depths of more than 250 km. The measurements provide limits for temperatures within the earth and a basis for extrapolation to greater depths. This report outlines experimental results for the melting of elements, minerals, and rocks under various conditions, in a dry state or in the presence of water and other volatile components. There is overlap with reports on experimental petrology in another section, but it is reduced to a minimum by limiting this review to melting curves and properties, without attention to the more detailed aspects of petrogenesis.

Luedemann and Kennedy [1968] measured the melting curves of lithium, sodium, potassium, and rubidium to 80-kb pressure. At about 60 kb they found rather sharp changes in the slope of the melting curves for lithium, potassium, and rubidium that could represent maximums in fusion curves analogous to the maximum previously discovered for cesium. The relationship between the temperature of melting for a given pressure and the compression measured at room temperature was discussed by Luedemann and Kennedy and Kennedy and Vaidya [1970]. The linear relationship for metals breaks down at pressures where maximums occur on the fusion curves. Gilbert [1969] found that the linear relationship does not appear to hold for silicate minerals. Kennedy and Vaidya proposed a re-evaluation of the various equations used to describe the effects of pressure on fusion temperatures. Extrapolation of melting curves for silicates or metals for estimation of melting temperatures in the deep mantle and core remains uncertain.

Between 1958 and 1964 the availability of the piston-cylinder apparatus had yielded melting curves to mantle pressures for a number of silicate minerals: albite, diopside, fayalite, forsterite, jadeite, and pyrope. Additional fusion curves for individual minerals and for

mineral assemblages have since been reported. The fusion curve for fayalite was measured to 40 kb by Hsu [1967] and extended to higher pressures above the olivine-spinel transition by Akimoto and Komada [1967]. Gilbert [1969] presented a melting curve for acmite to 45 kb. Using a differential thermal analysis technique with tungsten/rhenium thermocouples, Williams and Kennedy [1969] redetermined the melting curve of diopside, to 50-kb pressure. They claimed considerable improvement over existing methods employing quench techniques and platinum-rhodium thermocouples. Lindsley [1966, 1967] described melting relationships for sanidine and parts of the system  $\text{KAlSiO}_4$ - $\text{SiO}_2$  to 40 kb. Bell and Roseboom [1969] presented data for albite and jadeite and derived all theoretically possible types of  $P$ - $T$ - $X$  diagrams for melting at high pressures with four solid phases of different compositions (jadeite, albite, quartz, and nepheline) in a binary system ( $\text{NaAlSiO}_4$ - $\text{SiO}_2$ ). Luth [1969] presented the eutectic melting relationships for  $\text{NaAlSi}_3\text{O}_8$ - $\text{SiO}_2$  and  $\text{KAlSi}_3\text{O}_8$ - $\text{SiO}_2$  to 20 kb and found that the composition of the eutectic liquid was enriched in the feldspar component with increasing pressure. Bell and Davis [1969] described melting relationships in the system jadeite-diopside at 30 and 40 kb.

More complex silicate systems have been studied. Kushiro [1968] studied liquid compositions in a series of systems  $\text{Mg}_2\text{SiO}_4$ - $\text{SiO}_2$ - $X$ , where  $X$  represents  $\text{CaMgSiO}_4$ ,  $\text{CaAl}_2\text{O}_4$ ,  $\text{NaAlSiO}_4$ , and  $\text{MgAl}_2\text{O}_4$ . His results in the pressure range 7 to 40 kb were applied to the problem of the compositions of magmas formed at various depths by partial fusion of mantle peridotite. He described also the phase relationships in the system  $\text{Mg}_2\text{SiO}_4$ - $\text{CaMgSi}_2\text{O}_6$ - $\text{SiO}_2$  at 20 kb [Kushiro, 1969]. O'Hara and Yoder [1967] reviewed the formation and fractionation of basic magmas at high pressures by using results at 30 kb on the join  $\text{CaMgSi}_2\text{O}_6$ - $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$  and adjacent parts of the plane  $\text{CaSiO}_3$ - $\text{MgSiO}_3$ - $\text{Al}_2\text{O}_3$  and similar compositions obtained by mixing natural minerals separated from a garnet-peridotite nodule from a kimberlite. The effect of pressure on the system  $\text{MgO}$ - $\text{SiO}_2$ - $\text{TiO}_2$  was determined by MacGregor [1969]. Liquids became progressively richer in  $\text{TiO}_2$  as pressure increased to 40 kb. The melting relationships to 20 kb for the composition  $(\text{An}_{70}\text{Ab}_{30})_3\text{Fo}_1$  were determined by Emslie and Lindsley [1969], as a guide to anorthosite genesis.

Presnall [1969] presented a detailed geometrical analysis of partial fusion by using simple systems as examples.

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